Rheology of natural hydraulic limes for masonry repair

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Abstract The rheology of a series of mortars made with natural hydraulic limes (NHLs) from four manufacturers, commercially available in the UK, in conjunction with two Scottish sands, was determined. Rheologically, mortars conform to the Bingham model and the yield stress and plastic viscosity vary significantly between the various NHLs. As a consequence, when used on site, the water content necessary to achieve a consistent rheology varies over a two-fold range. Since site workers adjust water content to achieve a consistent rheology, this range will have a serious effect on the properties and performance of the hardened mortar in service.

1 Introduction

Cement mortar for repair of masonry causes severe damage and loss of historically-important fabric, so interest in the use of lime binders has grown. Lime mortars are more flexible and better able to accommodate expansion and contraction in the masonry, and are additionally perceived as more environmentally friendly than cements. Consequently, there is a demand in Scotland for the use of mortar made with natural hydraulic lime (NHL) to resist the prevailing environmental conditions.

Commercially available NHLs are classified according to their hydraulicity, being assigned to grades NHL2, NHL3.5 and NHL5 according to the strength achieved in an arbitrarily defined standard laboratory mortar [1]. However, users and specifiers of NHLs for masonry repair are hindered by a lack of information on practical mortars and the aim of this work was to contribute to a wider research programme giving experimentally based guidance on mix selection. The paper compares the rheology of mortars made with NHLs from four manufacturers, commercially available in the UK, in conjunction with two Scottish sands.

2 Materials and mixes

NHL2, NHL3.5 and NHL5 lime binders were obtained from four UK suppliers – Hanson (www.hanson.com), originating from France, Otterbein (http://www.zkw-otterbein.de), Germany, St Astier (www.stastier.co.uk), France, and Singleton Birch (http://www.lime-mortars.co.uk), Portugal. These NHLs were used with two sands – Loanleven, Perthshire, a mainly quartzitic sand, and Cloddach, Morayshire, predominantly granitic – in mortars of nominal proportions 1:2.5 lime:sand by volume. Figure 1 shows that the Cloddach sand's particle size distribution is slightly finer. Additionally, the relative bulk density of the Cloddach sand (1710 kg/m^3) is slightly lower than the Loanleven sand (1790 kg/m^3) and this implies a higher voids ratio. Table 1 shows the relative bulk densities of the NHLs, determined by the mean of three measurements of the mass of material in a 0.6L cylinder. Mortars were batched by mass of each material adjusted to ensure that the volume proportions remained constant.

Fig. 1 Particle size distribution of the sands

Table 1 Relative bulk densities of the NHLs (kg/m^3)

Grade	Hanson	Otterbein	St Astier	Singleton Birch
NHL2	630	520	570	510
NHL3.5	670	590	700	860
NHL5	-	510	730	830

3 Experimental procedure

3.1 Mixing

Approximately 1.5L of mortar was produced using the masses of the oven-dry sand and relevant NHL, calculated as above, mixed dry for one minute in a BS EN 196-1 mixer (Controls Instruments). Water was added over two minutes while rotating at low speed and mixing then continued until 7.5 minutes. At this point the mixing was stopped and material scraped off the walls of the bowl by hand before mixing for a further 7.5 minutes. Samples were taken for testing, then returned to the mixing bowl and more water added, mixed for a further two minutes and the sequence repeated. In this way the rheology of each mortar was measured at three progressively increasing water contents over a 30 minute period. A single replicate of each mix was prepared and tested (11 mortars, 33 tests).

3.2 Testing

The workability of each mortar at different water contents was determined with the Flow test according to BS EN 459-2 [2] and the rheology measured in the Viskomat NT instrument (Schleibinger, Germany) following the two-point principle [3,4]. The torque T exerted on a stationary paddle during rotation of a cylinder containing the mortar was measured as the speed of rotation N increased to 200 rev/min over 2 minutes and decreased to zero again over 2 minutes. Mortars conform to the Bingham model, with the intercept g corresponding to the yield stress and the slope of the line h corresponding to the plastic viscosity:

$$T = g + hN \qquad (1).$$

Calibration of the instrument enables the values of g and h determined from the flow curve to be converted to yield stress and plastic viscosity in fundamental units [2] but for the purposes of this paper it is sufficient to report g in Nmm and h in Nmms.

4 Results

The relationship between the water/binder ratio (W/B) and the Flow of each mortar is shown in Fig. 2 (Loanleven sand) and Fig. 3 (Cloddach sand).

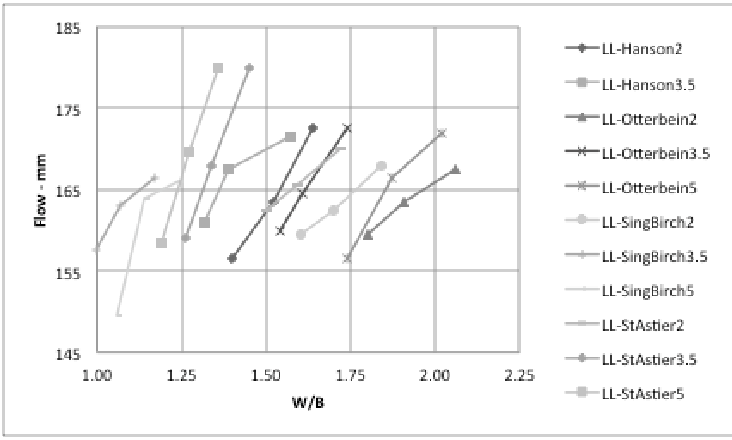

Fig. 2 Effect of water content on Flow of Loanleven mortars

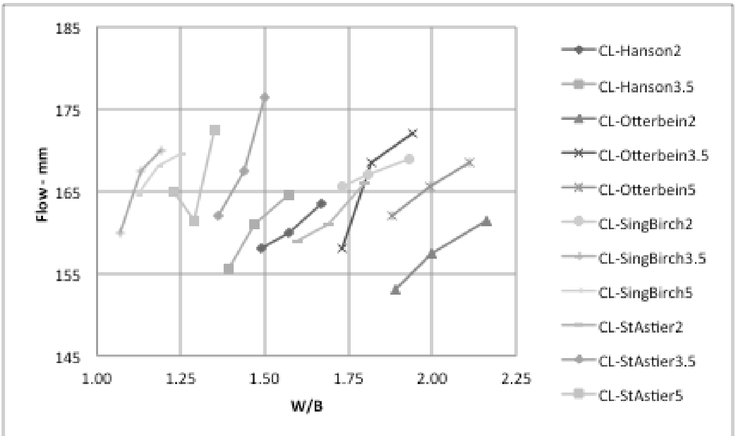

Fig. 3 Effect of water content on Flow of Cloddach mortars

Since Flow shows (with one exception) a linear trend against W/B these results can be summarised by a linear trend line, from which the W/B to give any desired Flow can be interpolated. Table 2 gives the W/B to achieve 165mm Flow for each mortar.

Table 2 Interpolated W/B for 165mm Flow. (Left – Loanleven / Right – Cloddach)

Grade	Hanson	Otterbein	St Astier	Singleton Birch
NHL2	1.53 / 1.72	1.97 / 2.26	1.57 / 1.78	1.76 / 1.70
NHL3.5	1.38 / 1.57	1.62 / 1.81	1.31 / 1.40	1.13 / 1.12
NHL5	-	1.88 / 1.98	1.24 / 1.27	1.20 / 1.12

The most obvious feature of the data in Table 2 is the wide range of W/B required by the different NHLs, even between those of the same grade. Overall, there is a factor of two between the highest and lowest W/B, with those of the same grade showing differences of between 30% and 55%. Cloddach requires more water than Loanleven sand for all of the Hanson, Otterbein and St Astier NHLs, which is consistent with Cloddach's finer particle size distribution, whilst there is no significant difference between the sands with Singleton Birch NHL. Comparing relative bulk densities (Table 1) there seems to be a parallel trend in the results for St Astier and Singleton Birch NHLs: in each case the NHL3.5 and NHL5 have a significantly higher relative bulk density than the NHL2 and in each case the W/B required is significantly lower. This is hard to explain because all the mortars were formulated on an equal volume basis, taking the relative bulk density into account.

Fig. 4 shows the general form of the flow curve of a lime mortar tested as described above in the Viskomat NT. The hysteresis loop between the up- and down-curves is due to the breakdown of structure formed by the flocculation of binder particles in water, and the parameters *g* and *h* are obtained by the best fit straight line through the points on the downcurve. Whereas the Flow is a single result, the best fit line permits the confidence limits to be estimated.

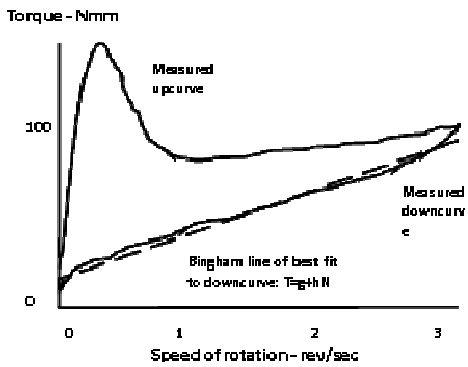

Fig. 4 Flow curve for lime mortar in the Viskomat NT

The relationships between W/B and *g* and between W/B and *h* are shown for Loanleven mortars in Fig. 5 and for Cloddach mortars in Fig. 6.

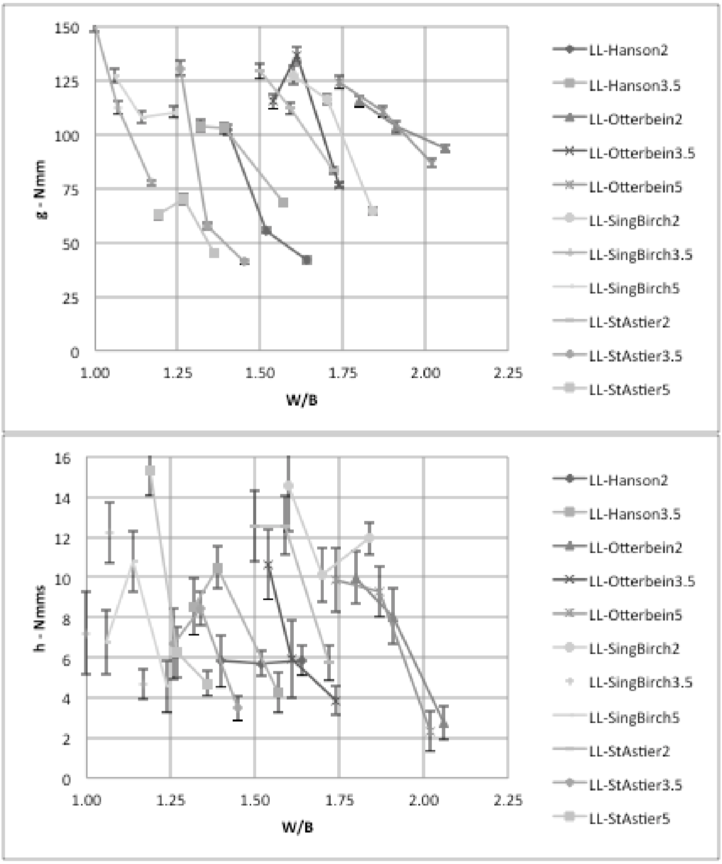

Fig. 5 Effect of water content on *g* (above) and *h* (below) of Loanleven mortars

The expected trend of a reduction in *g* with increasing W/B [2] is generally observed. However, in two Loanleven mortars and four Cloddach mortars *g* passes through a real maximum at the intermediate W/B, whilst in some others the difference between *g* at adjacent W/Bs is small. The 90% confidence limits for *h* can be calculated according to the method of Tattersall and Banfill [4], and are plotted at each point. It can be seen that in many cases the deviation from the expected trend of a reduction in *h* with increasing W/B [2] is within experimental error and in these cases the reduction in *h* is quite small over the range of W/B studied. The standard error in *g* under these test conditions is 1.93 times that in *h*, giving confidence limits of $\pm$2.5% of the value of g which are too narrow to plot on the graphs, and confirms the reality of the differences mentioned above. It can also be seen that, whilst the values of Flow and g are similar for mortars with both sands and accord with the well-established correlation between single-point tests such as Flow or slump and yield stress [4], the values of *h* and thus plastic viscosity are consistently lower for Cloddach sand than Loanleven sand mortars.

This is because the finer particle size distribution of the Cloddach sand enables the mortar to flow more easily, even when W/B has been controlled to give the same Flow and yield stress. This difference may manifest itself as easier spreading of the mortar in practice. These rheology measurements lead to the same conclusion as for the Flow test results: the NHLs require a wide range (up to two-fold) of W/B to achieve similar levels of yield stress and plastic viscosity.

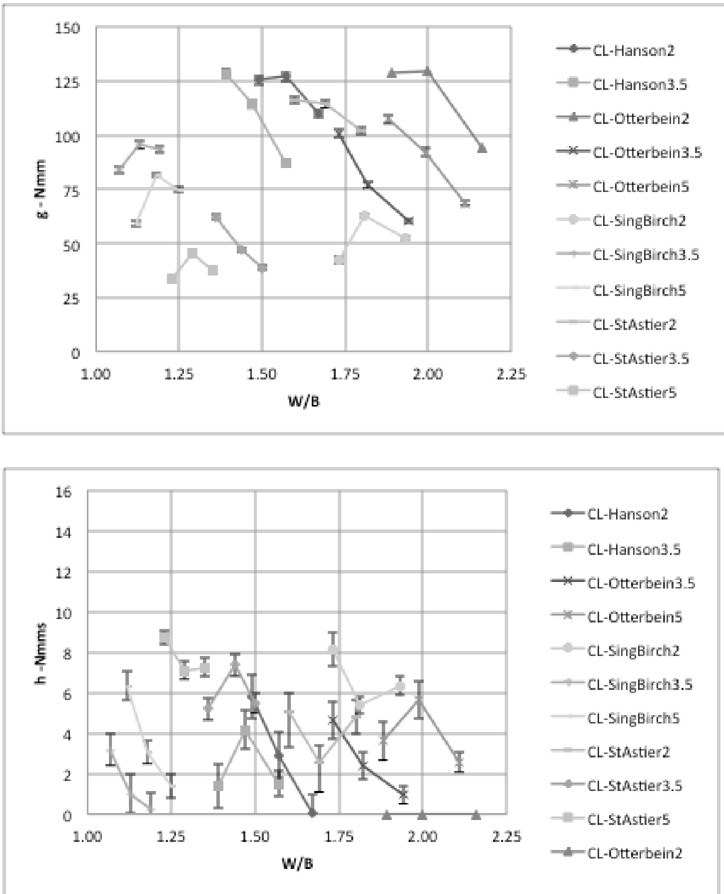

Fig. 6 Effect of water content on *g* (above) and *h* (below) of Cloddach mortars

5 Discussion

The implication of these wide variations in W/B between the different lime binders arises from the fact that on site the worker adjusts the W/B of the mortar to achieve the desired working properties. These working properties may be more or less well represented by Flow or rheology tests [2,5] but the relationship between the values given in these tests and W/B is clear. Table 2 shows that Otterbein NHL3.5 requires a 40-60% higher W/B than Singleton Birch NHL3.5 for the same workability and this difference in W/B is sufficient to halve the compressive strength of the mortar, suggesting that an Otterbein NHL3.5 mortar might perform like a NHL2 mortar in service. Similar, but not so large, differences in W/B occur between Otterbein and St Astier or Hanson NHLs and between St Astier or Hanson NHLs and Singleton Birch NHLs. Since compressive strength, flexural strength, elasticity, porosity and permeability are all related to W/B ratio and contribute to the long term performance of the mortar in use, these effects have the potential to lead to significant performance differences between NHLs that are graded as equivalent by the standard classification.

6 Conclusions

Not all natural hydraulic limes show the same rheological performance in mortar, even when they are given the same grading by the classification of BS EN 459-1. The water/binder ratio required for a given rheology using the eleven NHLs varies over a two-fold range and, even within the same grade (such as NHL3.5), there is up to a 40-60% variation in the required water/binder ratio. These variations have the potential to lead to significant differences in performance in site mortar.

7 Acknowledgements

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8 References

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